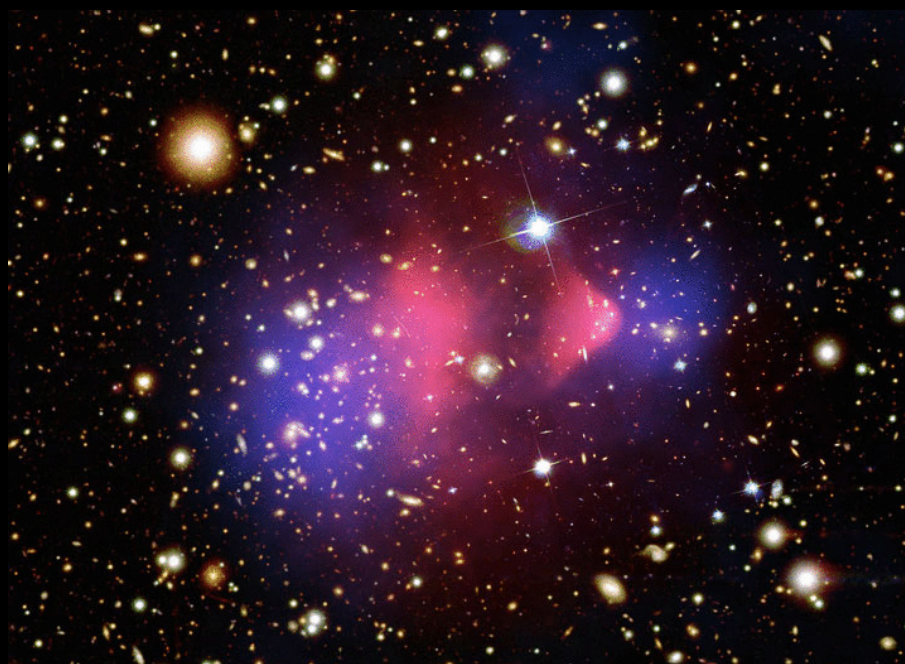


The Standard Model and Beyond

Hooman Davoudiasl

HET Group, Brookhaven National Laboratory



SULI Lecture, Physics Department, BNL

June 14, 2022

$$\hbar \approx 1.05 \times 10^{-34} \text{ J s} \quad ; \quad c \approx 3.0 \times 10^8 \text{ m/s}$$

$$\hbar = c = 1 \text{ in what follows}$$

Mass and Energy measured in eV

Length \leftrightarrow 1/Mass

GeV (Giga eV) = 10^9 eV

proton mass ≈ 1 GeV

TeV (Tera eV) = 10^{12} eV

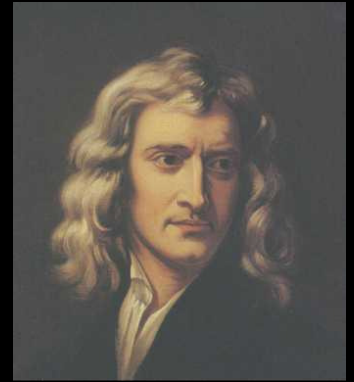
Everyday life:

Gravity and Electromagnetism (EM)



Falling Apple: Gravity

Well-described by Newtonian gravity



State of the Art: General relativity (GR)

- Spacetime curved by matter/energy.

Sun

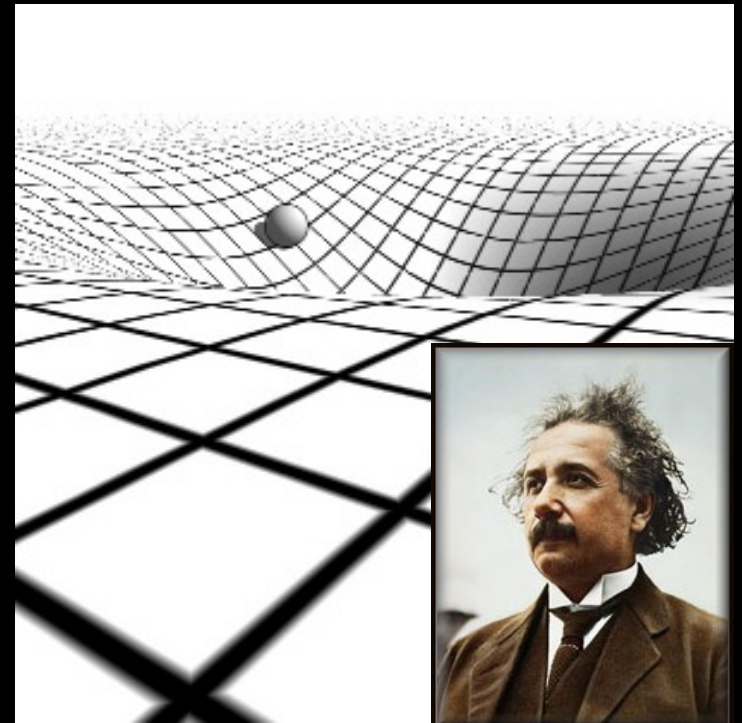
- Gravitational Force \rightarrow Geodesic.

Earth's Orbit

- Basis of modern cosmology.

Einstein's equations:

Curvature $\mathcal{G}_{\mu\nu} = 8 \pi G_N \mathcal{T}_{\mu\nu}$ Energy Distribution



G_N Newton's constant, $\mu, \nu = 0, 1, 2, 3$ (spacetime).

★ *Detection of Gravitational Waves* ★

- Directly confirmed a long-standing (~ 100 year) GR prediction
- Manifestation of the dynamical nature of spacetime



GW150914 (29, 36) M_{\odot}

GW151226 (8, 14) M_{\odot}

(SXS Project)

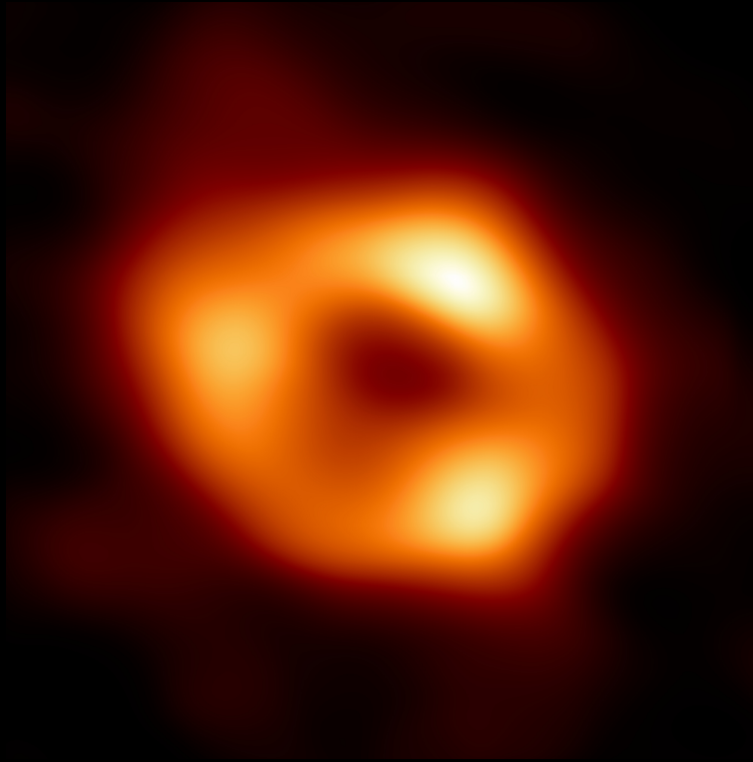
- Outstanding experimental achievement: measured strain (distance variation) $\sim 10^{-21}$! (highly sophisticated laser interferometry)
- 2017 Nobel Prize in Physics: Barish, Thorne, and Weiss



Shadow of M87*, Event Horizon Telescope

Mass: ~ 6.5 Billion Solar Masses ; Distance: ~ 55 Million Light Years

Results released April 10, 2019



Shadow of SgrA* (center of Milky Way), Event Horizon Telescope

Mass: ~ 4 Million Solar Masses ; Distance: ~ 27000 Light Years

Results released May 12, 2022

Q: Can we deduce something interesting about black holes by looking at the images?

Apple on the ground: Quantum Mechanics and EM

- Atoms in apple and ground: Electron *cloud* interactions stop the fall.
 - Pauli's exclusion principle for electrons; EM: repulsion.
- Atom: Nucleus (p and n) and electrons; Quantum Mechanics.
- Nuclear forces: weak and strong, not everyday, microscopic.
- Weak and EM forces \rightarrow Unified Electroweak Theory.

Summed up in the Standard Model of particle physics.



The Standard Model (SM):

Most precise description of microscopic physics

- **Gauge symmetry:** $SU(3)$ (strong) $\times SU(2) \times U(1)$ (electroweak)

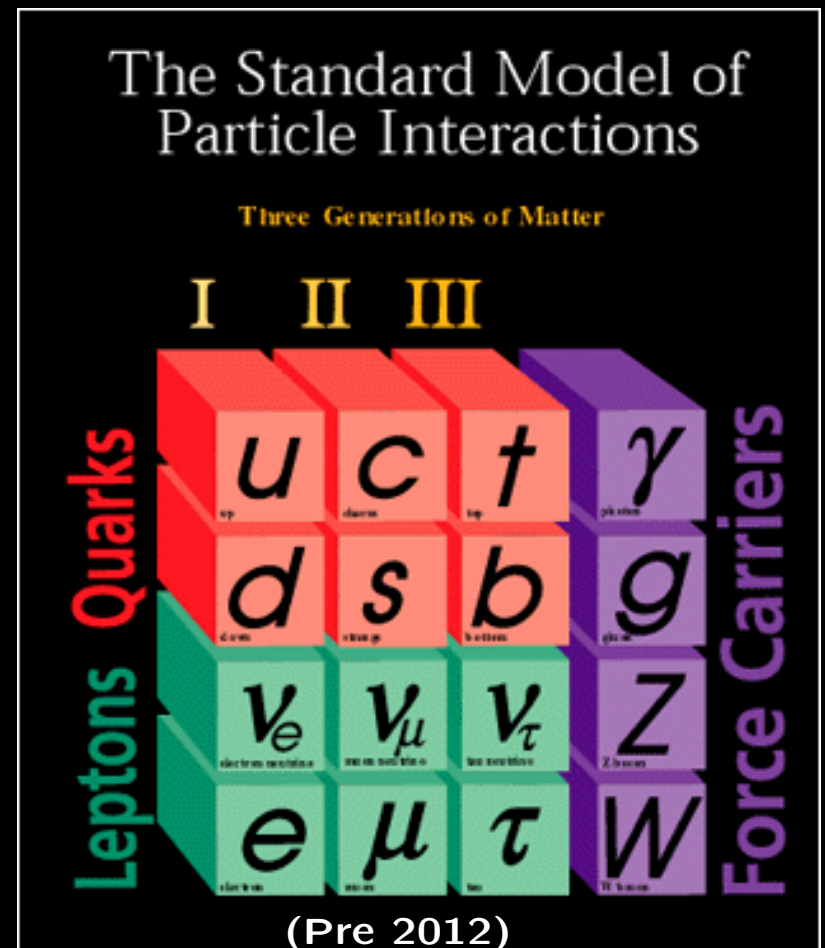
- **Elementary fermions, spin-1/2***

Quarks (+2/3, -1/3): Strong interactions

Leptons (0, -1): No strong interactions

- **Gauge Fields, spin-1**

Force mediators, generalized photons

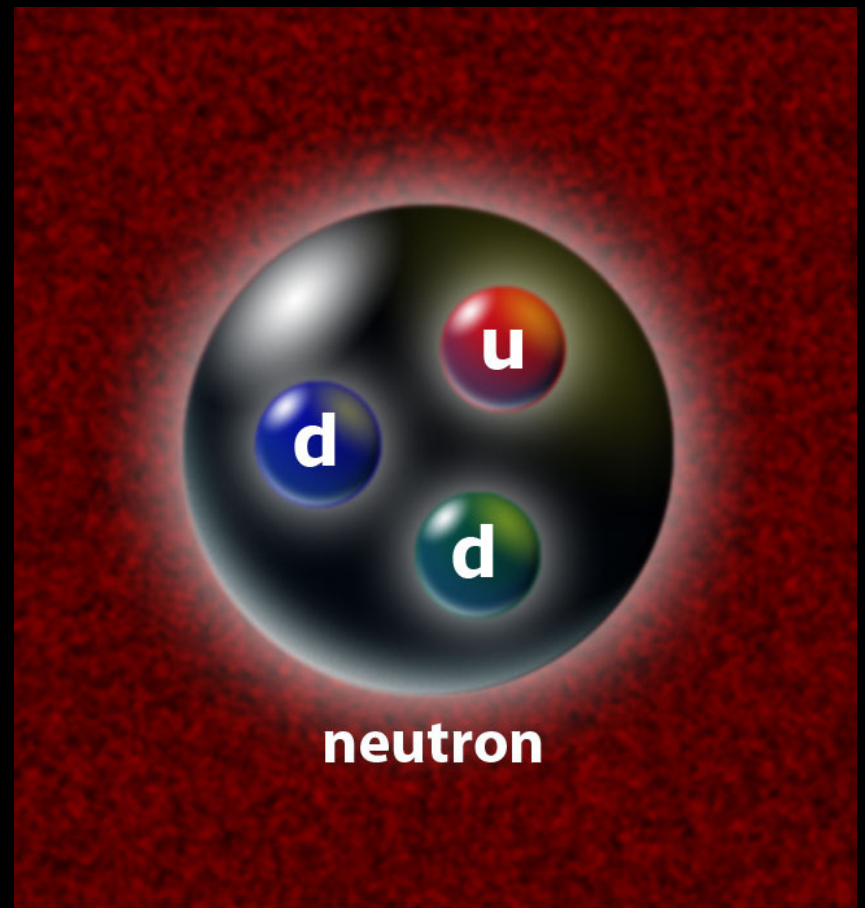
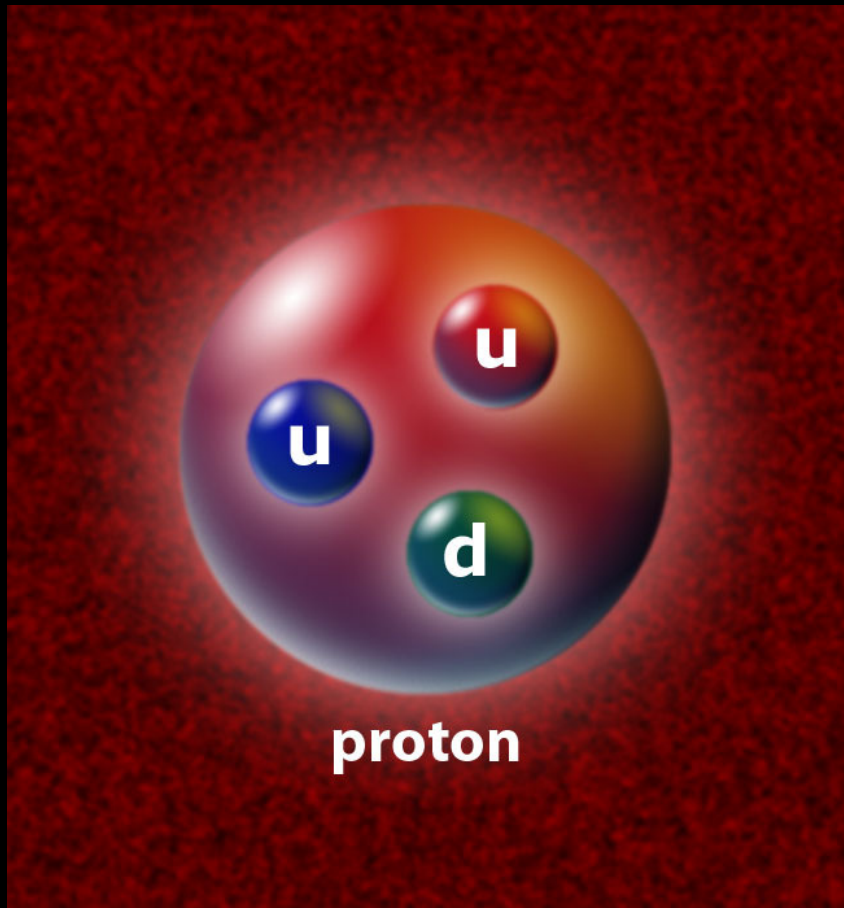


* Spin: intrinsic angular momentum (quantum mechanics)

Strong Interactions [$SU(3)$ (QCD)]:

QCD: Quantum Chromodynamics

- Short-ranged, confined to nuclear distances $\sim 10^{-15}\text{m}$
 - Gluons (g) bind quarks into **hadrons** (*hadros*: Greek for “bulky”):
 p , n , π^0 ($\bar{q}q$), . . .

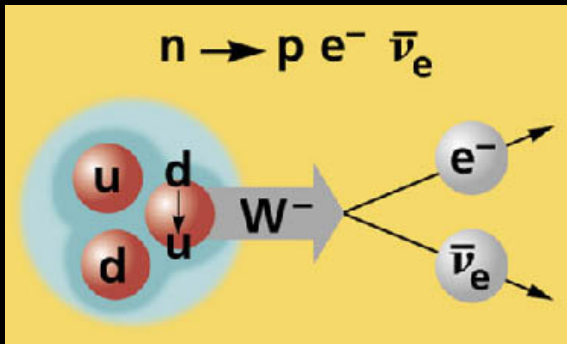


Electroweak Interactions [$SU(2)_L \times U(1)_Y$]:

- Spontaneously broken to EM

\Rightarrow Massive W^\pm ($80.4 \text{ GeV}/c^2$), Z^0 ($91.2 \text{ GeV}/c^2$)

Short-ranged: $\Delta x \sim c \Delta t \sim c \times \frac{\hbar}{mc^2} \sim 10^{-18} \text{ m}$ (energy-time uncertainty)



Q: Why are there stable neutrons in atomic nuclei?

- EM: $U(1)_{EM}$ (QED)

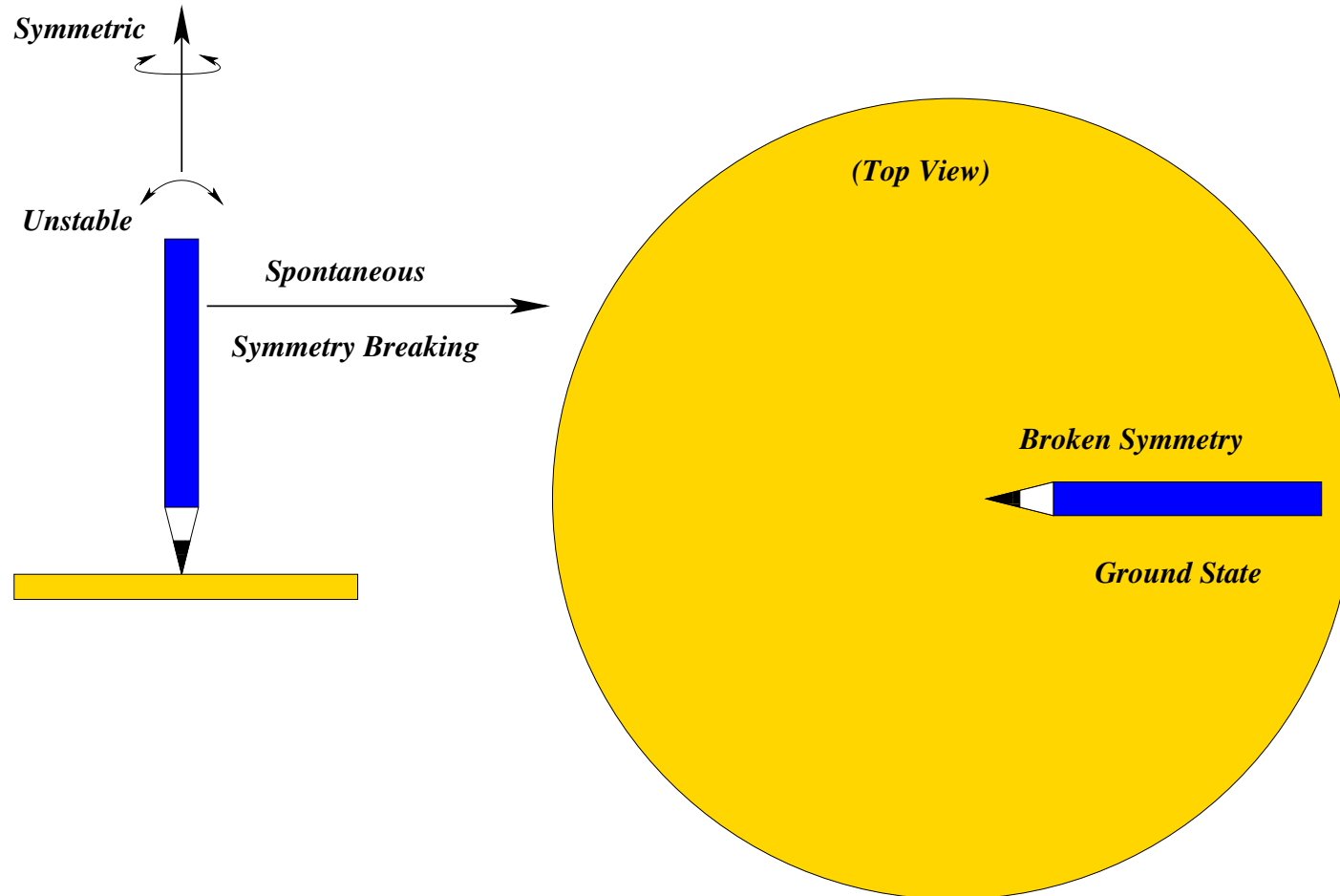
Massless photon, γ , long-ranged



Tabletop Spontaneous Symmetry Breaking

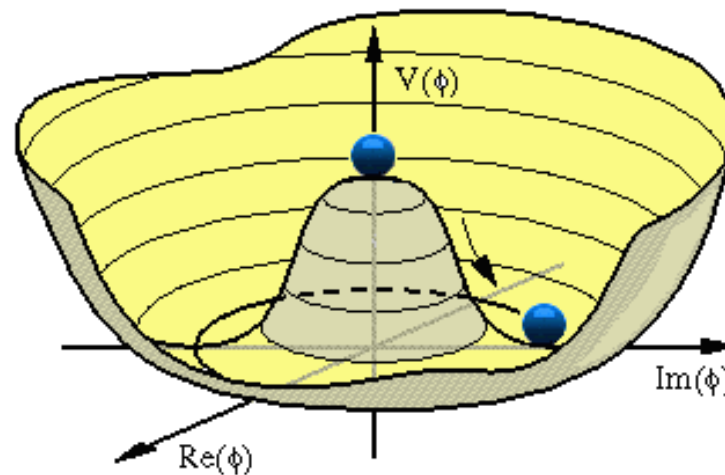
A pencil, standing on its tip: unstable, falls to its “ground state”.

- Underlying theory: rotationally symmetric, no preferred direction.
- The pencil spontaneously picks an orientation, breaks the symmetry.



Electroweak Symmetry Breaking in SM

- Higgs (H) boson condensation $\langle H \rangle \neq 0$.
- Elementary particle masses from interactions with $\langle H \rangle \neq 0$:
 - $m_W, m_Z, m_{\text{fermion}} \propto \langle H \rangle$
 - Fermion flavor: $m_t/m_u \sim 10^5$! (Why?)
- $\boxed{m_\nu = 0}$ (Strongly disfavored by data!)



Q: How much of the “visible” mass in Universe is from Higgs?

July 4th, 2012, discovery announced at CERN

Scalar (spin-0) H boson discovered at the LHC, mass ~ 125 GeV

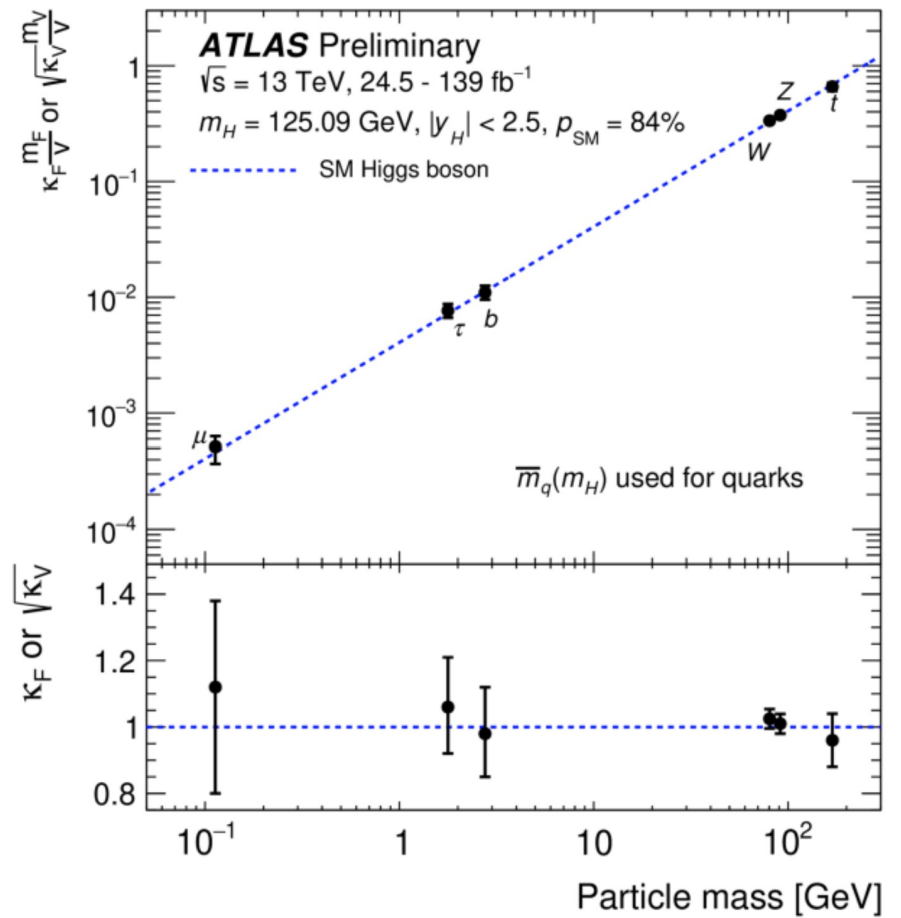
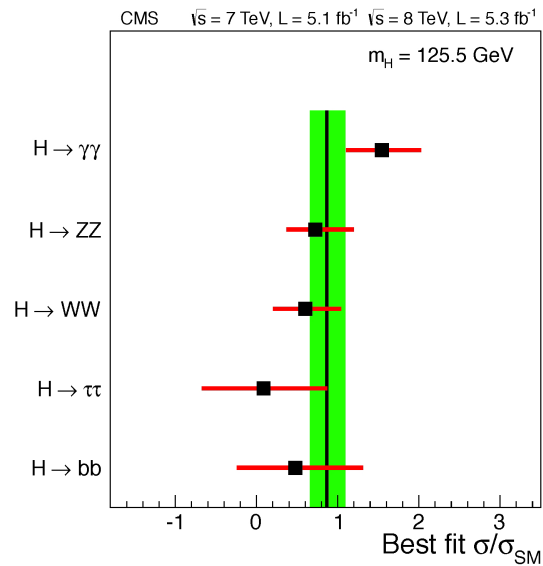
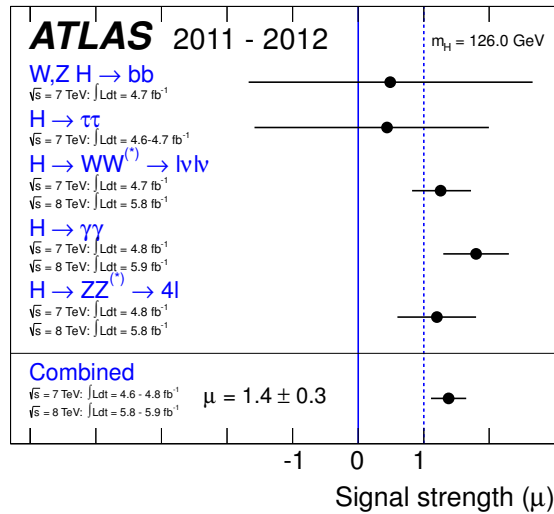
LHC: pp collider Design beam energy: 2×7000 GeV

Circumference (km): 26.659



2×6500 GeV Run finished in 2018

2×6800 GeV Run: Summer 2022

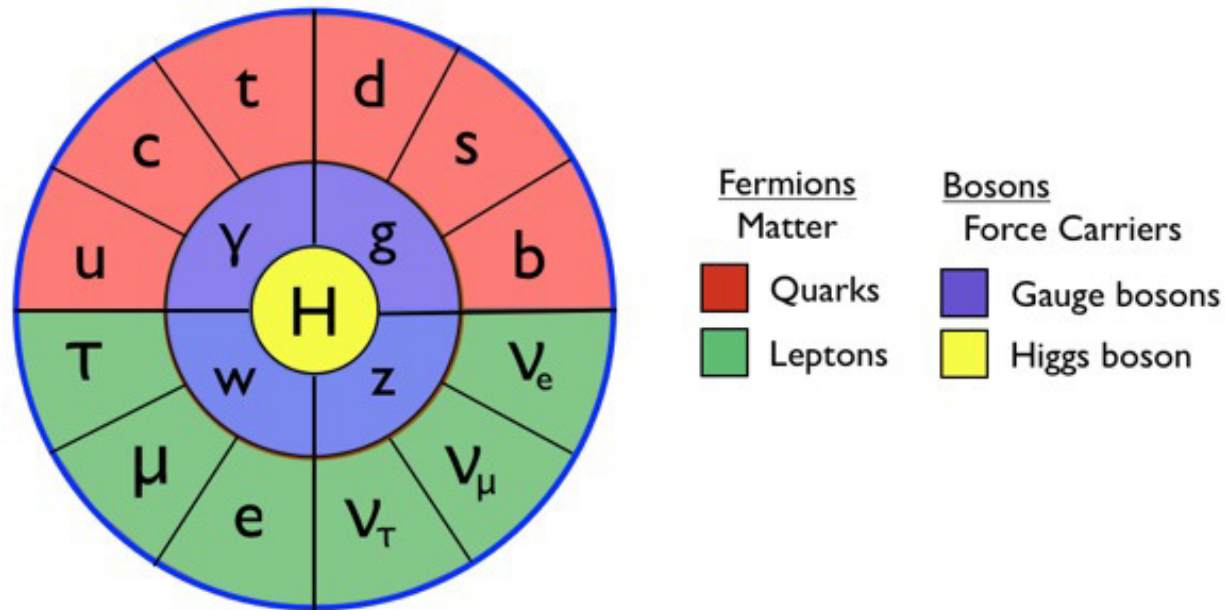


(Image: ATLAS Collaboration/CERN)

Early Run 1: $\sim 10 \text{ fb}^{-1}$

Q: What is significant about having the muon in the plot?

SM + GR \Rightarrow Great Success!



Particles of the Standard Model

Nearly all* measurements in agreement with SM+GR.

* Except, for example, potential hints from muon $g - 2$ (Lecture by Bill Morse, 6/21/2022), some B meson (bound state of b quark with a light quark) decays,...

* Recent CDFII (Tevatron detector; shut down in 2011) result for measured W mass; 7σ away from SM expectation (!)(?)

SM: An Incomplete Description of Nature

- Theoretical Hints

Why is gravity so weak?

Why is the neutron electric dipole moment so small?

...

- Experimental Evidence

Non-zero neutrino masses, dark matter, ...

Conceptual Mystery: Why is gravity so weak?

Force between e and p in an atom: $\frac{F(\text{Grav})}{F(\text{EM})} \sim 10^{-40}!$

Gravity: the weakest known interaction

Newton's Constant: $G_N = 6.67 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2}$

Gravity scale: Planck mass

$$M_P \equiv (\hbar c / G_N)^{1/2} \approx 10^{19} \text{ GeV} \sim (10^{-35} \text{ m})^{-1} !$$

(mass \leftrightarrow 1/length; uncertainty)

$$M_P \gg m_W \quad (\hbar = c = 1)$$

\Rightarrow Hierarchy problem: one may expect quantum effects to push Higgs mass (m_W) close to M_P ; Higgs mass seems “unnatural”

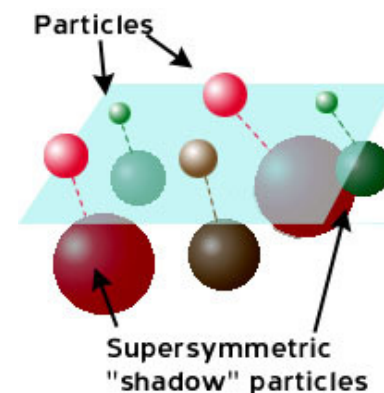
Hierarchy and New Physics Near m_H

- Strong Interactions near m_H

- Composite Higgs (analogue of a QCD hadron)
- Extra dimensions (lowering the fundamental mass scale of gravity by diluting it in compact extra dimensions)

- Supersymmetry: Fermions \leftrightarrow Bosons.

- Quantum effects on $\langle H \rangle$ cancel



- *So far, no firm evidence at LHC for new physics near $m_H \approx 125$ GeV*
- *New physics elusive, or perhaps “naturalness” not the right guide*

Strong Empirical Evidence for Beyond SM

- **Neutrino Flavor Oscillations** Lecture by P. Denton, 6/17/2022

- Solar, atmospheric, and terrestrial laboratory data:

$$m_\nu \lesssim 10^{-6} m_e$$

- Simple extension: right-handed* neutrinos ν_R

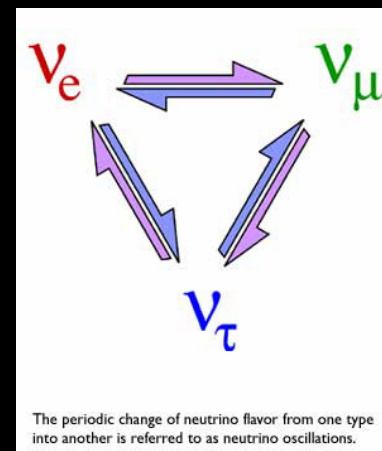
* Spin and momentum aligned

- Typically, difficult to test:

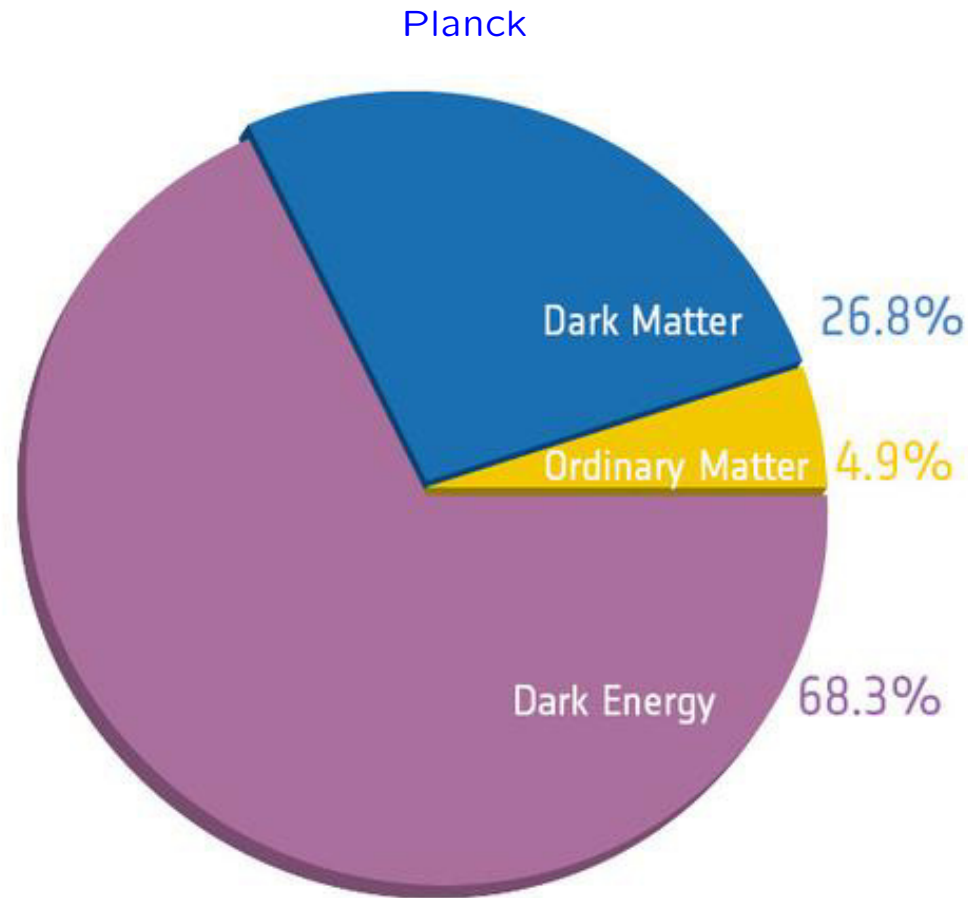
- ν_R very massive or else negligible coupling to SM

- **Cosmology**

- Dark Matter: neutral, cosmologically stable



Cosmos: 95% unknown!



Cosmic acceleration (dark energy):

Could be vacuum energy (cosmological constant); no dynamics

Visible (Everyday) Matter

PERIODIC TABLE
Atomic Properties of the Elements

Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

Planck constant h 6.626 070 15 × 10⁻³⁴ J s (exact)
 speed of light in vacuum c 299 792 458 m s⁻¹ (exact)
 elementary charge e 1.602 176 634 × 10⁻¹⁹ C (exact)
 electron mass m_e 9.109 383 56 × 10⁻³¹ kg
 proton mass m_p 1.672 621 63 × 10⁻²⁷ kg
 fine-structure constant α 1/137.036
 Rydberg constant R_∞ 10 973 732 m⁻¹
 Boltzmann constant k 1.380 658 × 10⁻²³ J K⁻¹

Solids
 Liquids
 Gases
 Artificially Prepared

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce
Physics Laboratory
Standard Reference Data Group
physics.nist.gov
www.nist.gov/srd

1 H Hydrogen 1.00794 1.008 1.008	2 He Helium 4.002602 4.0026 4.0026																	18 Ar Argon 39.948 39.948 39.948
3 Li Lithium 6.941 6.94 6.94	4 Be Beryllium 9.012182 9.0122 9.0122																	19 K Potassium 39.0983 39.098 39.098
5 Na Sodium 22.989769 22.9898 22.9898	6 Mg Magnesium 24.304 24.304 24.304																	20 Ca Calcium 40.078 40.078 40.078
7 Al Aluminum 26.981538 26.9815 26.9815	8 Si Silicon 28.0855 28.0855 28.0855																	21 Sc Scandium 44.955910 44.9559 44.9559
9 P Phosphorus 30.973761 30.9738 30.9738	10 S Sulfur 32.06 32.06 32.06																	22 Ti Titanium 47.88 47.88 47.88
11 Cl Chlorine 35.453 35.453 35.453	12 Ar Argon 39.948 39.948 39.948																	23 V Vanadium 50.9415 50.9415 50.9415
13 Ga Gallium 69.723 69.723 69.723	14 Ge Germanium 72.64 72.64 72.64																	24 Cr Chromium 51.9961 51.9961 51.9961
15 In Indium 114.818 114.818 114.818	16 Sn Tin 118.710 118.710 118.710																	25 Mn Manganese 54.938044 54.9380 54.9380
17 Tl Thallium 204.3833 204.383 204.383	18 Pb Lead 207.2 207.2 207.2																	26 Fe Iron 55.845 55.845 55.845
19 Bi Bismuth 208.98038 208.9804 208.9804	20 Po Polonium (209) (209) (209)																	27 Co Cobalt 58.933194 58.9332 58.9332
21 At Astatine (210) (210) (210)	22 Rn Radon (222) (222) (222)																	28 Ni Nickel 58.6934 58.6934 58.6934
23 Fr Francium (223) (223) (223)	24 Ra Radium (226) (226) (226)																	29 Cu Copper 63.546 63.546 63.546
25 Ac Actinium (227) (227) (227)	26 Th Thorium (232) (232) (232)																	30 Zn Zinc 65.38 65.38 65.38
27 Pa Protactinium (231) (231) (231)	28 U Uranium (238) (238) (238)																	31 Ga Gallium 69.723 69.723 69.723
29 Np Neptunium (237) (237) (237)	30 Pu Plutonium (244) (244) (244)																	32 Ge Germanium 72.64 72.64 72.64
31 Am Americium (243) (243) (243)	32 Cm Curium (247) (247) (247)																	33 As Arsenic 74.9216 74.9216 74.9216
33 Bk Berkelium (247) (247) (247)	34 Cf Californium (251) (251) (251)																	34 Se Selenium 78.96 78.96 78.96
35 Es Einsteinium (252) (252) (252)	36 Fm Fermium (257) (257) (257)																	35 Br Bromine 79.904 79.904 79.904
37 Md Mendelevium (258) (258) (258)	38 No Nobelium (259) (259) (259)																	36 Kr Krypton 83.799 83.799 83.799
39 Lr Lawrencium (262) (262) (262)	40 103 Untriseptium (263) (263) (263)																	37 Rb Rubidium 85.4678 85.4678 85.4678
																		38 Sr Strontium 87.62 87.62 87.62
																		39 Y Yttrium 88.90584 88.9058 88.9058
																		40 Zr Zirconium 91.224 91.224 91.224
																		41 Nb Niobium 92.90638 92.9064 92.9064
																		42 Mo Molybdenum 95.94 95.94 95.94
																		43 Tc Technetium (98) (98) (98)
																		44 Ru Ruthenium 101.07 101.07 101.07
																		45 Rh Rhodium 102.90550 102.9055 102.9055
																		46 Pd Palladium 106.42 106.42 106.42
																		47 Ag Silver 107.8682 107.8682 107.8682
																		48 Cd Cadmium 112.411 112.411 112.411
																		49 In Indium 114.818 114.818 114.818
																		50 Sn Tin 118.710 118.710 118.710
																		51 Sb Antimony 121.757 121.757 121.757
																		52 Te Tellurium 127.60 127.60 127.60
																		53 I Iodine 126.90447 126.9045 126.9045
																		54 Xe Xenon 131.29 131.29 131.29
																		55 Cs Cesium 132.90545 132.9054 132.9054
																		56 Ba Barium 137.327 137.327 137.327
																		57 La Lanthanum 138.90547 138.9055 138.9055
																		58 Ce Cerium 140.116 140.116 140.116
																		59 Pr Praseodymium 140.90765 140.9076 140.9076
																		60 Nd Neodymium 144.24 144.24 144.24
																		61 Pm Promethium (145) (145) (145)
																		62 Sm Samarium 150.36 150.36 150.36
																		63 Eu Europium 151.964 151.964 151.964
																		64 Gd Gadolinium 157.25 157.25 157.25
																		65 Tb Terbium 158.92534 158.9253 158.9253
																		66 Dy Dysprosium 162.50 162.50 162.50
																		67 Ho Holmium 164.93032 164.9303 164.9303
																		68 Er Erbium 167.259 167.259 167.259
																		69 Tm Thulium 168.93402 168.9340 168.9340
																		70 Yb Ytterbium 173.04 173.04 173.04
																		71 Lu Lutetium 174.967 174.967 174.967
																		72 Hf Hafnium 178.49 178.49 178.49
																		73 Ta Tantalum 180.94788 180.9479 180.9479
																		74 W Tungsten 183.84 183.84 183.84
																		75 Re Rhenium 186.207 186.207 186.207
																		76 Os Osmium 190.23 190.23 190.23
																		77 Ir Iridium 192.222 192.222 192.222
																		78 Pt Platinum 195.084 195.084 195.084
																		79 Au Gold 196.96657 196.9666 196.9666
																		80 Hg Mercury 200.59 200.59 200.59
																		81 Tl Thallium 204.3833 204.3833 204.3833
																		82 Pb Lead 207.2 207.2 207.2
																		83 Bi Bismuth 208.98038 208.9804 208.9804
																		84 Po Polonium (209) (209) (209)
																		85 At Astatine (210) (210) (210)
																		86 Rn Radon (222) (222) (222)
																		87 Fr Francium (223) (223) (223)
																		88 Ra Radium (226) (226) (226)
																		89 Ac Actinium (227) (227) (227)
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																		91 Pa Protactinium (231) (231) (231)
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																		93 Np Neptunium (237) (237) (237)
																		94 Pu Plutonium (244) (244) (244)
																		95 Am Americium (243) (243) (243)
																		96 Cm Curium (247) (247) (247)
																		97 Bk Berkelium (247) (247) (247)
																		98 Cf Californium (251) (251) (251)
																		99 Es Einsteinium (252) (252) (252)
																		100 Fm Fermium (257) (257) (257)
																		101 Md Mendelevium (258) (258) (258)
																		102 No Nobelium (259) (259) (259)
																		103 Lr Lawrencium (262) (262) (262)

Based upon ^{12}C . () indicates the mass number of the most stable isotope.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2003)

- ~ 5% of energy budget
- Baryonic: protons, neutrons
- Asymmetric: $\Delta B \neq 0$ (negligible anti-matter today)

Generation of Baryon Asymmetry

- Requires Sakharov's conditions for *baryogenesis*:
 - (i) Baryon number violation
 - (ii) C and CP violation (distinguishing particles from anti-particles)
 - (iii) Departure from equilibrium
- Conditions absent [(iii)] or not at sufficient levels [(ii)] in the SM
- ΔB small, $n_B/n_\gamma \sim 10^{-9}$, but still too big to explain!

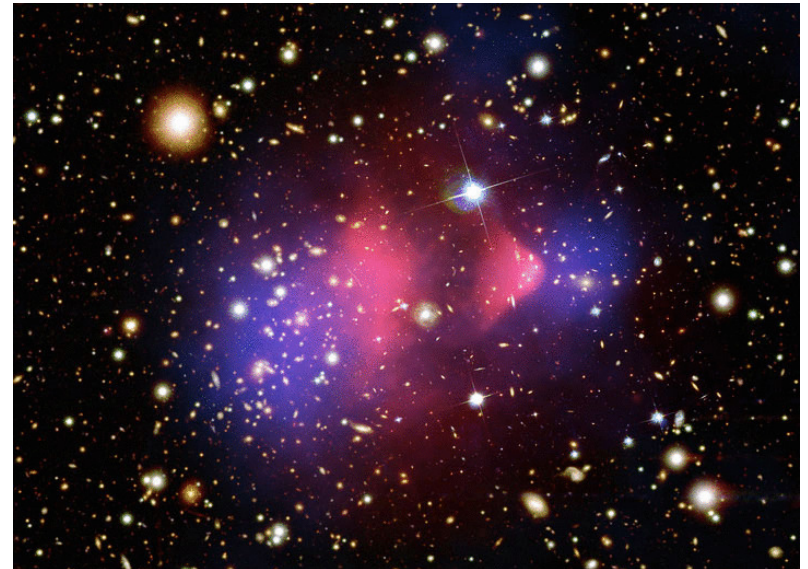
 \Rightarrow New Physics
- Could be related to neutrino mass generation (heavy ν_R states)

Dark matter (DM)

- $\sim 27\%$ of energy density
- Robust evidence from cosmology and astrophysics
 - CMB, BBN, rotation curves of galaxies, lensing, Bullet Cluster, ...
- **Unknown origin**
 - Feeble interactions with atoms and photons
 - Self-interactions not strong ($\sigma \lesssim 1$ barn)
 - Not explained in SM

Strongly motivates new physics

So far, evidence limited to gravity effects



How do you look for something of unknown nature?



Possible DM mass scale: $10^{-22} \text{ eV} \lesssim M_{\text{DM}} \lesssim 10^{68} \text{ eV}$
(~ 90 orders of magnitude!)

Q: Why is there a lower bound ($\sim 10^{-22} \text{ eV}$)?

Searches often guided by *theoretical motivation*

- **Example: The hierarchy problem in SM:**

- New particles with masses $M_{\text{new}} \gtrsim M_H (\approx 125) \text{ GeV}$: supersymmetry, ...
- Energy scale often referred to as the “weak scale” (weak interactions)

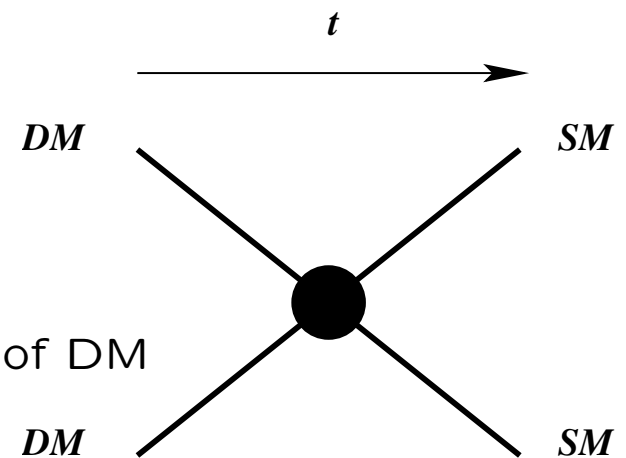
⇒ **Weakly Interacting Massive Particles** (WIMPs)

- Thermal relic density: annihilation, freeze-out

- $\rho_{\text{WIMP}} \propto 1/\sigma_{\text{ann}}$
- $\sigma_{\text{ann}} \sim g^4/M^2$
- $g \sim g_{\text{weak}}, M \gtrsim \text{weak scale}$: roughly the right amount of DM

- Weak scale theoretically motivated

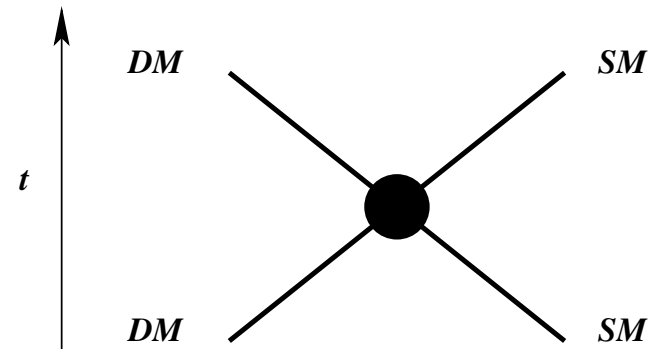
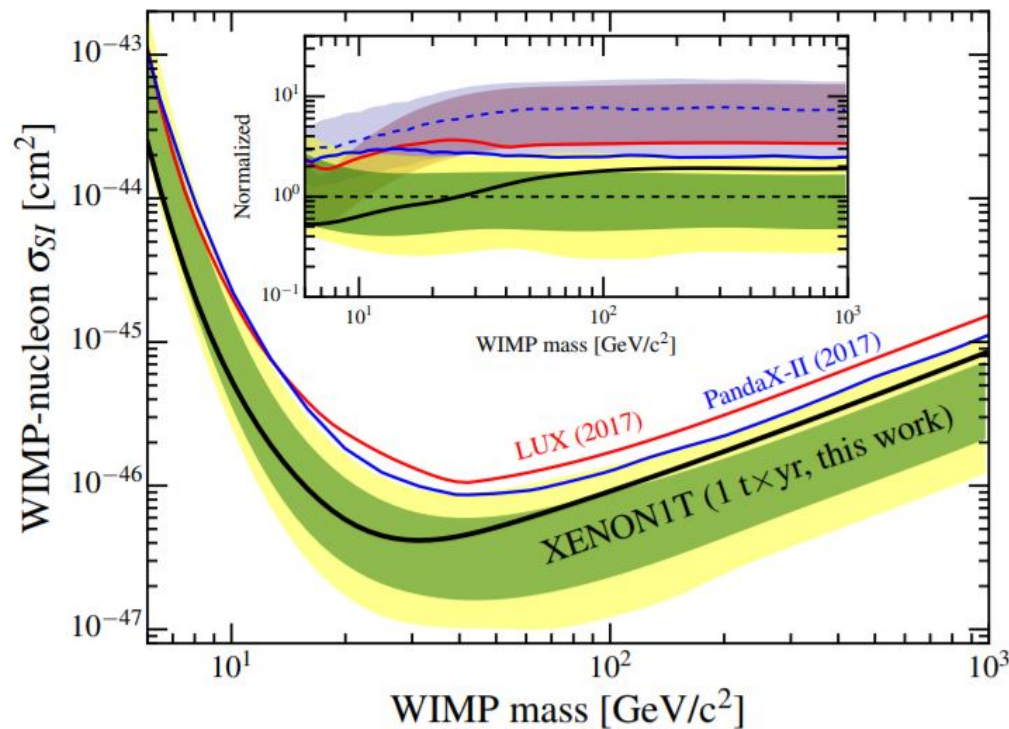
- However, g^4/M^2 may be achieved otherwise (WIMPless Miracle)



Feng and Kumar, 2008

Direct WIMP DM Searches

- WIMPs: have been a main focus of DM searches
- Recoil off atomic nuclei (electrons)

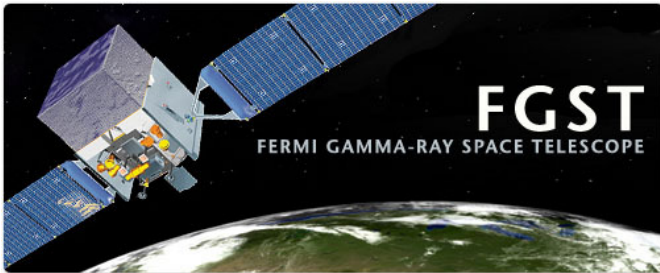


E. Aprile *et al.* [XENON Collaboration], Phys. Rev. Lett. **121**, no. 11, 111302 (2018)

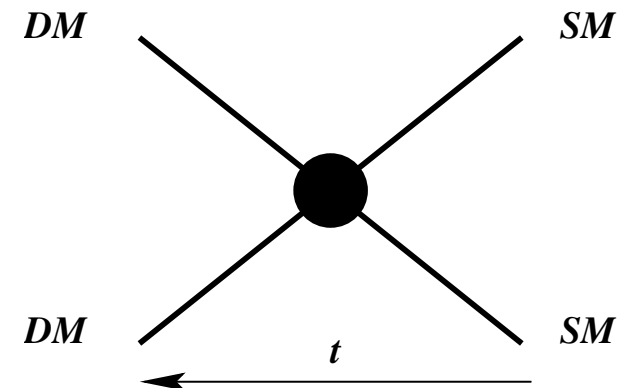
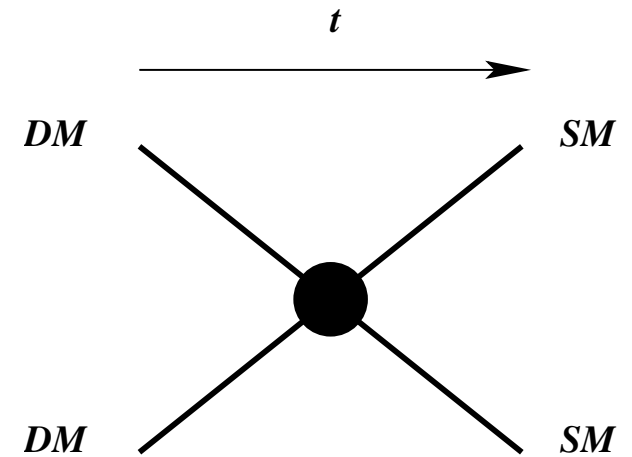
Q: Why do the constraints get weaker towards lower and higher DM masses?

Other avenues for WIMP search:

- Indirect searches: self-annihilation signals
 - Related to thermal relic density
 - Complicated by astrophysical backgrounds



- Collider production: LHC
 - Search for missing energy in events



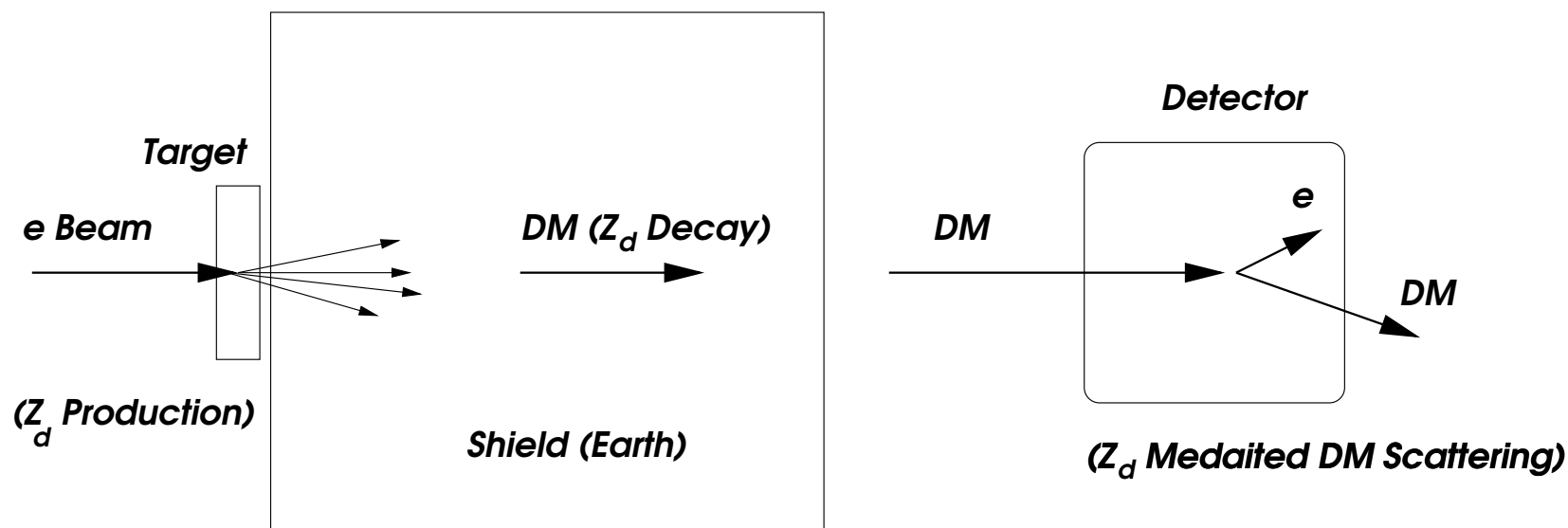
Dark Sectors and Dark Forces

For example: [Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008](#)

- With lack of evidence for new physics near weak scale, other DM scenarios have been put forth in recent years
- Example: DM could be light and may reside in a separate sector with its own forces
 - Analogy with SM
- DM interactions with SM are indirect
- Simple possibility: a “dark” sector $U(1)_d$
 - Mediated by vector boson Z_d of mass m_{Z_d} coupling g_d
- $m_{Z_d} \lesssim 1$ GeV has been invoked in various contexts
 - DM interpretation of astrophysical data, explaining some potential deviations (e.g. muon $g - 2$)

Invisible Z_d and Low Mass DM Production

- Possible production and detection of *DM beams* in experiments
Batell, Pospelov, Ritz, 2009 (p beam); Izaguirre, Krnjaic, Schuster, Toro, 2013 (e beam dump)
- Interesting probe of GeV-scale DM (challenge for direct detection)



Motivated a search at Fermilab:

“Dark Matter Search in a Proton Beam Dump with MiniBooNE”

A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. Lett. **118**, no. 22, 221803 (2017)

Concluding Remarks

★ Standard Model and GR successfully describe wide range of phenomena.

- Higgs boson discovered at LHC, appears to complete SM
- Some potential deviations in current data
- In particular, muon $g - 2$ could be hinting at new physics; more data and further theory investigations are needed

★ SM conceptual difficulties: hierarchy (Higgs mass “naturalness”),...

- No firm evidence for any new physics associated with a “natural” Higgs mass
- Perhaps still early, but new organizing principles may be needed

★ Empirical shortcomings: neutrino masses, dark matter, baryogenesis, ...

- Neutrino mass generation: requires physics beyond SM, but typically elusive
- Dark matter: robust gravitational evidence for new physics, potentially accessible
- WIMP dark matter: Motivated by “naturalness” of m_H (under strain)
- Wide range of other possibilities for DM currently viable

...I am induced by many reasons to suspect that they [phenomena of nature] may all depend upon certain forces by which the particles of bodies, by some causes hitherto unknown, are either mutually impelled towards each other, and cohere in regular figures, or are repelled and recede from each other; which forces being unknown, philosophers have hitherto attempted the search of nature in vain; but I hope the principles here laid down will afford some light either to this or some truer method of philosophy.

Sir Isaac Newton (1643-1727)

(Preface to Principia)